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LABORATORY SIMULATION OF FLASH-BUTT WELDING OF RAIL (INTERIM REPORT)

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LABORATORY SIMULATION OF FLASH-BUTT WELDING OF RAIL

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by

D.M. Fegredo, L.E. Collins and J.T. Bowker

ABSTRACT

Laboratory simulation of the flash-butt welding of eight rail steels of varying Cr (0-0.81 wt%) and Mo (0-0.20 wt%) contents has been carried out on an MMC Dilatometer and a Gleeble 1500 machine. The critical cooling rate, at which a fine pearlitic structure of hardness HRC ≈ 38 is produced, was determined for each steel. Similar results were obtained in both dilatometer and Gleeble simulations. It was found that whereas both Cr and Mo significantly reduce the critical cooling rate at which a fully pearlitic structure is obtained, Mo has the larger effect.

LABORATOIRES DE RECHERCHE EN MÉTALLURGIE PHYSIQUE
RAPPORT: LRMP 85-39(TR)

SIMULATION EN LABORATOIRE DU SOUDAGE EN BOUT PAR ÉTINCELAGE D'ACIERS À RAIL

(Rapport intérimaire)

par

D.M. Fegredo, L.E. Collins et J.T. Bowker

RÉSUMÉ

La simulation en laboratoire du soudage en bout par étincelage de huit aciers à rail ayant un contenu varié en Cr (0 à 0,81 % en poids) et en Mo (0 à 0,21 % en poids) a été réalisée au moyen d'un dilatomètre MMC et du simulateur Gleeble 1500. La vitesse critique de trempe à laquelle on obtient une structure perlitique de dureté 38 HRc a été déterminée pour chaque acier. Les simulations au moyen du dilatomètre et du simulateur Gleebe ont donné des résultats semblables. On a découvert que bien que Cr et Mo réduisent considérablement la vitesse critique de trempe à laquelle on obtient une structure constituée entièrement de perlite, Mo a l'effet le plus important.

INTRODUCTION

In flash-butt welding the ends of two pieces to be welded are heated by the passage of an electric current and subsequently, forged together [1]. During the heating phase, a steep temperature gradient is established along the length of both pieces. The highest temperatures occur at the abutting surfaces (flashing surfaces) and rapidly decrease in the vicinity of the jaws which clamp the material to be welded. In the region of the jaws, the temperature is at, or near, ambient temperature.

Flash-butt welding was first used in 1937 to produce continuous-welded rail (CWR) [2] and the practice has steadily increased since. The process is used primarily for welding rail in the plant, although Hauser [2] reported (in 1976) that an in-track welding unit had been developed and evaluated. In rail-plant flash-butt welding, the rails are first preheated by resistance heating. The rail ends are alternately brought into contact (to promote high current flow; e.g., 20,000 to 100,000 A at ~ 5-10 V) and separated up to 20 times during the pre-heating stage. This procedure raises the temperature at the end of the rail to 950-1100°C and flashes off rough points. After the rail ends reach the correct temperature, flashing is initiated again and the movable platen is accelerated to upset the rail ends to the point of refusal either with a constant platen speed or under an impact load of 530-580 kN (119-130 ksi). A minimum upset of 12.7 mm is recommended.

Rail steel hardenability varies with composition. The current AREA specification [3] for standard C-Mn rail of nominal weight > 121 lb/yd (60 kg/m) requires a composition of 0.69/0.82 % C, 0.70/1.00 % Mn and 0.10/0.25 % Si. Pearlite forms in this steel at cooling rates less than ~ 16°C/s at 705°C. Vines et al. [4] report natural flash-butt weld cooling rates of ~ 0.7-2°C/s but this range presumably applies to Australian conditions. It is likely that rates of ~ 1.5-2.5°C/s are obtained under Canadian conditions but standard rail steel welds will always be pearlitic. Alloying (Mn, Cr, V, Mo) to produce a premium rail at rail-mill hot bed cooling rates acts by increasing hardenability. As a result, bainite and even martensite may form in some alloy premium rails following flash-butt welding. However, in lean-alloy premium rails, tailored to respond to mildly accelerated cooling, pearlite of hardness ~ HRC 38 should form in flash-butt welds without post-weld heat treatment. Good CWR productivity is achieved with matching weld and base material hardness.

Plant flash-butt weld cooling rates can be simulated in laboratory experiments on sub-size specimens which lend themselves to detailed examination. Examples include specimens for (a) end-quench, (b) dilatometer and (c) Gleeble tests:

(a) Standard end-quench (Jominy) bars are 1-in. (25.4 mm) diam., 3-in. (76.2 mm) long cylinders austenitized and quenched from one end at a fixed quench rate. Hardnesses are determined at 1/16-in. (1.6 mm) intervals along the length of the bar from the quenched end on a ground flat 0.015-in. (0.38 mm) deep. Microstructures can be determined on transverse sections corresponding to any particular cooling rate and hardness.

(b) Specimens 10 mm long and 6 mm diam. are austenitized and then subjected to programmed Newtonian cooling in a MMC quench-deformation dilatometer. Phase transformations are indicated by perturbations to smooth changes in sample length. Hardness and microstructure are subsequently determined on transverse sections of cooled specimens.

(c) A Gleeble 1500 machine, initially designed for the study of weld heat-affected-zones, can simulate virtually any thermomechanical metallurgical process. In the current work, 10 mm x 10 mm x 70 mm specimens are austenitized and subjected to programmed cooling. The austenitizing temperature and programmed cooling conditions are monitored at the specimen centre because the temperature drops off rapidly towards the grips at either end. For the same reason, evaluations of the microstructure and hardness is limited to a 5 mm wide band at the centre.

This report describes the effects of different cooling rates from a fixed austenitizing temperature on the subsequent hardness and microstructure of dilatometer and Gleeble specimens of various experimental rail steels. The objective of the work, which continues, is to correlate laboratory experiments with in-plant flash-butt welding processes that produce similar properties. Once complete, this work should enable weld conditions in the plant to be specified by low-cost laboratory tests.

EXPERIMENTAL PROCEDURE

The cooling rates to produce ~ HRC 38 pearlite in 51 eutectoid alloy steel compositions by end-quench experiments have already been determined and reported [5]. These cooling rates, reported at 705°C, served as starting points for most of the preliminary dilatometer experiments.

According to information received, from the CN rail flash-butt welding plant in Belleville, Ont., standard, 136 lb/yd (67.6 kg/m) C-Mn rails are heated to 1000°-1100°C in 60 s, upset for ~ 10 s and cooled in air. Alloy rails are preheated in 65-70 s, upset for ~ 10 s, cooled in air to 700°-750°C, held for 10 s60 s and then cooled freely to room temperature.

In dilatometer and Gleeble simulations, specimens were heated to 1050°C in 60 s, held at temp. for 35 s and then program-cooled. Deformation is not included in the simulated cycle (flash-butt weld). Dilatometer experiments were done under vacuum or inert atmosphere. From the dilatometer cooling curves, average cooling rates between 800°C and 500°C were determined and the conditions producing fine pearlite of hardness ~ HRC 38 were subsequently applied to the initial Gleeble work. The PMRL Gleeble machine does not compute theoretical cooling curves and requires time-temperature cooling data to be "programmed in". For this reason, initial Gleeble experiments used dilatometer specimen data. However, because exothermic phase transformations can cause perturbations, future Gleeble experiments will utilize theoretical Newtonian time-temperature cooling data.

Hardness measurements and metallographic examination were done by standard techniques on transverse sections of dilatometer specimens. Sections from the centre of the 10 mm length were examined. Water-cooled grips, 30 mm apart, hold the ends of the Gleeble specimens. Consequently, a sharp temperature gradient occurs from the centre of the 30 mm specimen length to the front face of the grips. Calibration with Pt-Pt 13% Rh thermocouples has shown that, for an austenitizing temperature of 1300°C, the temperature is within $\pm$ 10°C over a 5 mm wide band at the centre of the 30 mm distance between the grips [8]. The uncertainty in temperature at the centre of length should be even less, of course, at lower austenitizing temperatures such as 1050°C used here. A fiducial line is scribed on one surface at the centre of length of each specimen before testing, Fig. 1, and temperatures at the centre

of the line are monitored by a pyrometer during the test. Hardness measurements are made on the marked surface, ~ 1 mm from the line, Fig. 1, and metallographic examination was done on the opposite side within the 5 mm band with the fiducial line as a guide.

EXPERIMENTAL RESULTS

The chemical compositions of the eight experimental, eutectoid steels are given in Table 1. A complete summary of pertinent dilatometer test results is given in Table 2. Two cooling rate criteria are included; the first is the average cooling rate between 800°C to 500°C, the second is the cooling rate at 705°C. End-quench cooling rates at 705°C that produce ~ HRC 38 pearlite are also given in the table. These are taken from Reference 5. Cooling rate data for Steel G were obtained from earlier work [6] and for steel H from the accelerated-cooling (spray) of hot-rolled plates [5]. Table 2 also includes results of hardness measurements.

Newtonian cooling rates that produce ~ HRC 38 pearlite in dilatometer specimens, Table 2, were used in initial Gleeble experiments. The results are given in Table 3. Hardness values (see Fig. 1 for location) and descriptions of microstructures produced are also included. Some examples of Gleeble microstructures obtained in the 5 mm wide central band are shown in Fig. 2 (a-i).

DISCUSSION

Table 2 shows that, in general, lower cooling rates are required to produce fully pearlitic structures of hardness ~ HRC 38 in dilatometer specimens than in end-quench specimens. Three reasons may account for the difference:

(i) End-quench cooling rates were not determined on individual specimens of varying composition [5] but from the calibration of one composition of high hardenability. The exothermic heat of transformation to pearlite in compositions of lower hardenability will decrease cooling rates in the transformation range 600°C-700°C.

(ii) Imposed, computer controlled cooling rates are better maintained in small dilatometer specimens of small thermal mass.

(iii) Although end-quench cooling rates were obtained on fully killed steels (Al additions) austenized at 1010°C, in the present work, most steels were austenitized at 1050°C. In particular, no Al was added to steel D (see Table 1). The larger prior austenite grain size formed at 1050°C will increase hardenability and reduce the cooling rate required for transformation to fully pearlitic structures.

An excellent correlation exists between the hardness and metallographic results from the dilatometer and Gleeble machines, Table 3. Further Gleeble experiments are planned.

Examples of fully pearlitic microstructures are shown in Fig. 2 (a,b,c,f,h). Steel D was not "killed" with Al and a relatively small amount (0.015% Al) was added to steel A. This enlarged the prior austenite grain sizes in these two steels, Fig. 2 (a,c). Steel D has an austenite grain size of ~ ASTM 3 1/2-4, Fig. 2(d), as indicated by ferrite outlines. The effect of V in reducing austenite grain size is apparent, Fig. 2(h). Figures 2(d), 2(e) and 2(g) demonstrate the effect of increasing alloy content in reducing the cooling rate required for full transformation to pearlite of hardness ~ HRC 38. Thus, fully pearlitic structures form for cooling rates of 110°C/s, 60°C/s and 25°C/s in steel C (0.61% Cr) Fig. 2(b), steel D (0.80% Cr) Fig. 2(c) and steel F (0.81% Cr- 0.11% Mo) respectively, whereas, mixed microstructures result when cooling rates of 100°C/s, 60°C/s and 25°C/s are respectively applied to steel D, Fig. 2(d), steel F, Fig. 2(e) and steel G (0.75% Cr0.20% Mo). The effect of Cr and Mo additions on the critical quench rate (for HRC 38 pearlite) is also reflected in the dilatometer dilatation - temperature results. Chromium significantly reduces the critical rate, Fig. 3, but the addition of Mo to the Cr-bearing alloys produces a larger effect than for an equivalent wt% addition of Cr. This indicates the stronger effect of Mo in suppressing the austenite to pearlite transformation.

REFERENCES

1. Metals Handbook, 9th Edition, Vol. 6, "Welding, brazing and soldering", ASM, 1983.

2. D. Hauser, "Rail steels, development, processing and use", ASTM STP 644, Philadelphia, Pa. (1978), pp. 118-141.

3. Specifications for Steel Rails, American Railway Engineering Association Specifications, 1978, 59E Van Burns St., Chicago, Ill., 60616.

4. M.J. Vines, P.H. Townend, G. Lancaster and S. Marich, 1st International Heavy Haul Conference, Perth, Australia, 1978, Session 411, Paper H.6.

5. D.M. Fegredo, W.A. Pollard, E.F. Connors and D.R. Kiff, Can. Met. Quart., 22(4), 1983, 453-474.

6. D.M. Fegredo & D.R. Kiff, "A comparison of microstructures and mechanical properties of forged and rolled laboratory plates and rails of similar composition", CANMET Report MRP/PMRL-79-10(1R), February 1979.

7. Private communication from A. Marshall, Canadian National Railways, December 1983.

8. J. Bowker, "Simulation of metallurgical processes", CANMET Report MRP/PMRL 83-24(TR), April 1983.

ACKNOWLEDGEMENTS

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Table 1 - Compositions

Steel	C	Mn	Si	Al	Cr	Mo	V	S	P
A	0.68	0.89	0.22	0.015	-	-	-	0.015	0.009
B	0.68	0.76	0.35	0.05	0.37	-	-	0.027	0.010
C	0.73	0.80	0.33	0.035	0.61	-	-	0.03	0.01
D	0.71	0.69	0.28	-	0.80	-	-	0.004	0.004
E	0.70	0.79	0.29	0.05	0.64	0.07	-	0.035	0.01
F	0.73	0.78	0.27	0.015	0.81	0.11	-	0.01	0.01
G	0.69	0.83	0.29	0.06	0.75	0.20	-	0.016	0.013
H	0.65	1.08	0.82	-	0.51	-	0.11	0.03	0.009

Table 2 - Summary of Dilatometer Test Results

Steel	EQ rate* °C/min at 705°C	Test No	** $t_{800-500°C}$ s	Dilameter test cooling rate °C/min $\frac{60 \times 300}{t_{800-500}}$	at 705°C	P_s + °C	Hardness HRC	Microstructure++ From dilatation vs. temperature	Microstructure++ From optical examination.
A	~500	19	45	400	449	610	32	P	P
		30	36	500	609	605	31.5	P	P
		36	24	750	858	605	34.5	P + B(?)	~100% P(B)
B	~250	1	73	257	281	625	36.3	P	95% P; 5% B
		7	36	500	609	570	50.2	P + B + 90% M	20% B,P; 80% M
		14	60	300	335	605	38	P + M(?)	90% P; 10% B,M
		20	90	200	227	635	35	P + 5% B	90% P; 10% B,M
		31	120	150	169	632	35.5	P	P
		39	102.9	175	200	660	36.5	P	P
C	~100	24	120	150	165	620	40.5	80% P; 20% B	70% P; 30% B(M)
		29	150	120	134	622	33.5	P + 5% B	95% P; 5% B,WS)
		32	180	100	114	640	37	P	P
		40	163.6	110	122	670	39	P	95 + % P(WS)
D	150	21	150	100	114	612	42	25% P; 75% B	15% P; 70% B; 15% M
		27	240	75	86	625	39	90% P; 10% B	50% P; 50% B
		33	360	50	56	660	35.5	P	P
		41	300	60	71	670	41	P	P
E	140	25	300	90	103	620	39	80% P; 20% B	70% P; 30% B(WS)
		29	240	75	86	635	39.5	P + 5% B	90% P; 10% B
		34	360	50	56	655	33	P	~100% P(B)
		42	277	65	72	675	38.5	P	90 + % P; B(M)
F	≤100	22	514.3	35	39	646	42	P + 5% B(?)	90% P; 10% B
		35	720	25	28	645	39	P	P
G	(<30)	23	1800	10	11.3	640	36.5	P	98% P; 2% B
		36	1200	15	17	640	38.5	75% P; 25% B	75% P; 25% B
H	(≥170)	26	180	100	114	647	40	P	P
		37	144	125	141	635	41.5	P + M(?)	75% P; 25% M

* End-quench cooling rates producing ~ HRC 38 pearlite. End-quench experiments not done on steels G and H.

** Time in seconds to cool from 800°C to 500°C.

+ Start of pearlite transformation in °C.

++ P-pearlite; B-bainite; M-martensite; WS-white streaks of martensite due to alloy segregation.

Table 3 - Summary of Gleeble Test Results

Steel	Newtonian Cooling Rate °C/min	Hardness HRC	Microstructure
A	* 750	38-39	95% P; 2% B; 3% WS
B	* 175	38-39	P
C	* 110	40-41	P
	175	$43\frac{1}{2}$-$44\frac{1}{2}$	75% P; 5% B; 20% M
D	* $60\frac{1}{2}$	41-42	P
	100	$39\frac{1}{2}$-$44\frac{1}{2}$	75% P; 25% B
E	* 65	39-40	95% P; 5% B
	100	41-42	75% P; 25% B; M
F	* 25	41-42	95% P; WS
	60	45	10% P; 60% B; 30% M
G	* 10	35	P
	25	$39\frac{1}{2}$-40	25% P; 75% B; M
H	* 100	$41\frac{1}{2}$-42	95% P; 5% M
	110	42-$42\frac{1}{2}$	P
	175	49-50	40% P; 60% M

* Dilatometer cooling rates from Table 2 producing ~ HRC 38 pearlite.

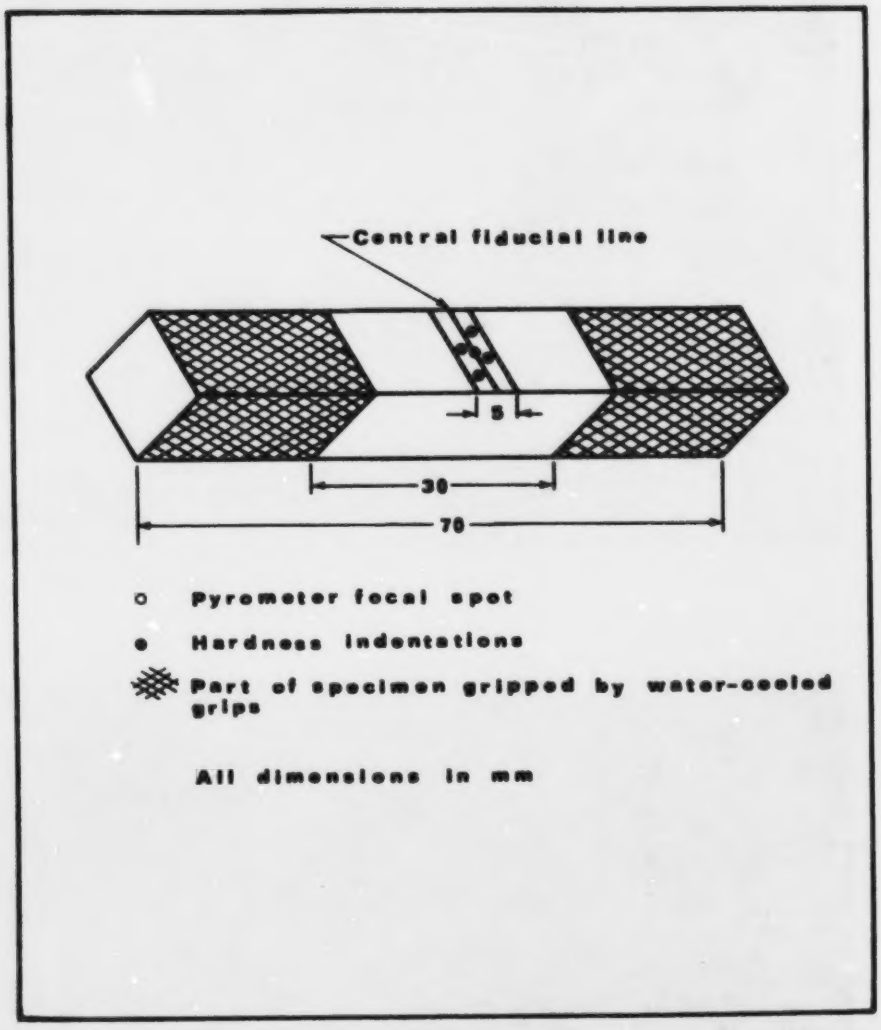
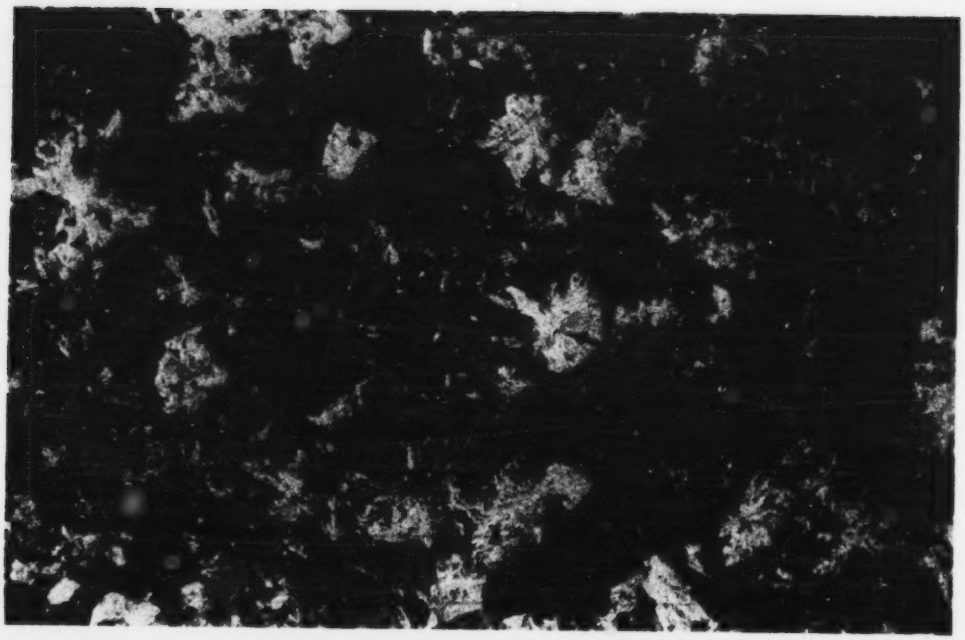


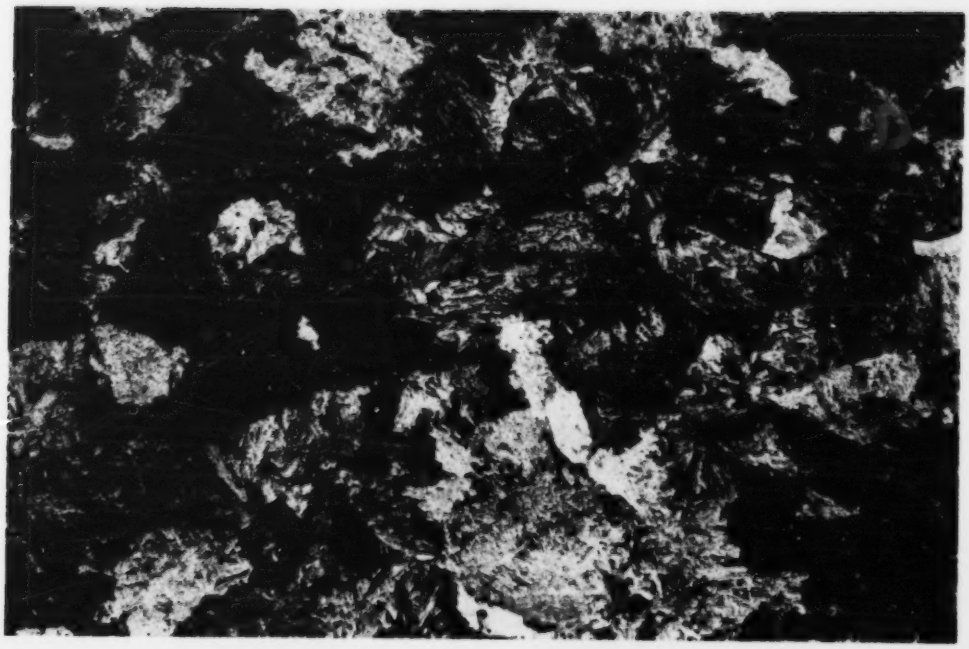
Fig. 1 Gleeble test bar



a) Steel A - 750°C/min

b) Steel C - 110°C/min

Fig. 2. cont'd.

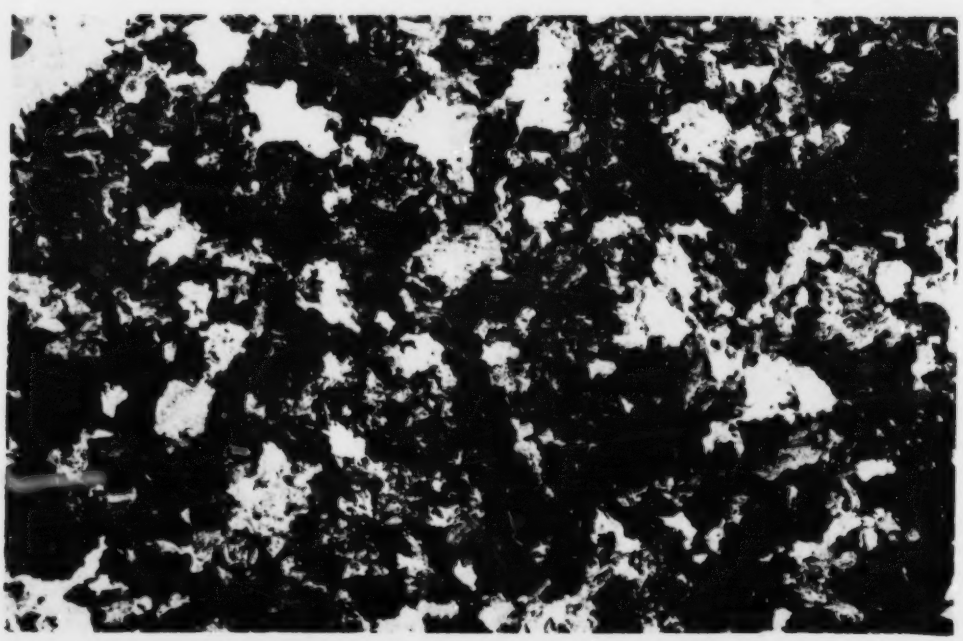


c) Steel D - 60°C/min

d) Steel D - 100°C/min

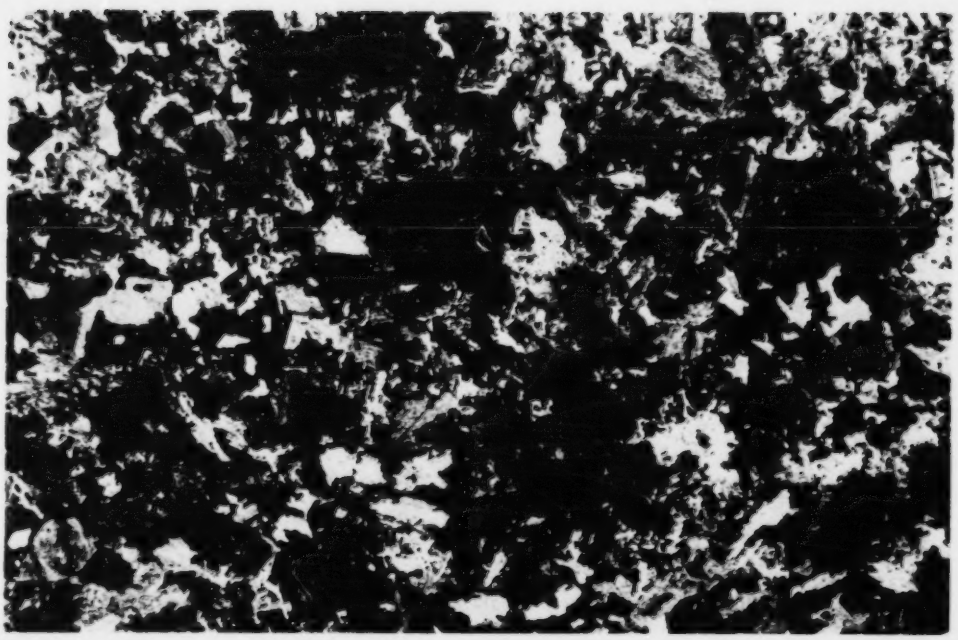
Fig. 2. cont'd.

e) Steel F - 60°C/min



f) Steel G - 10°C/min

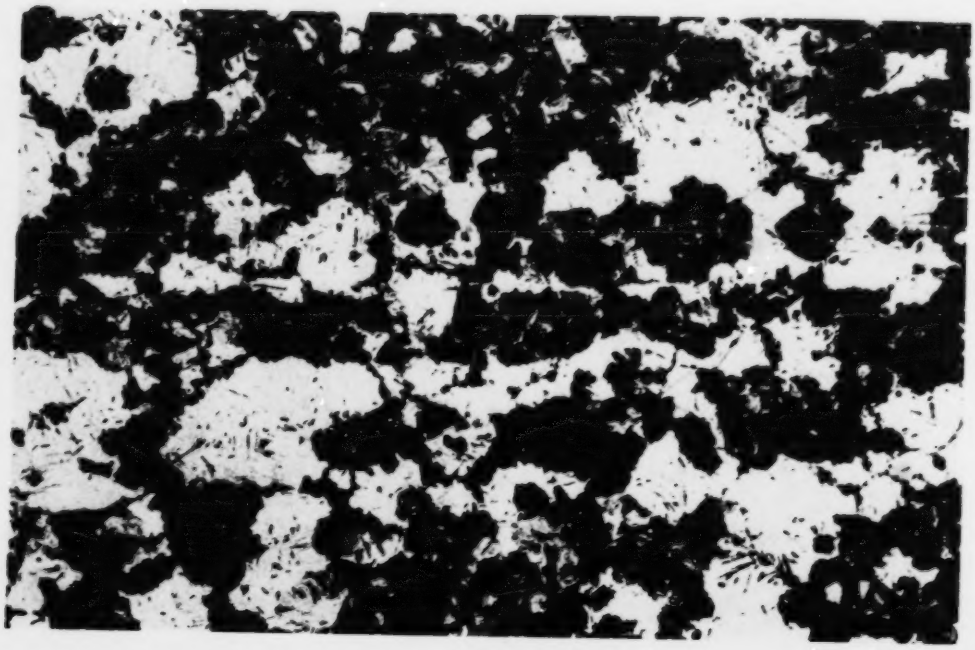
Fig. 2. cont'd.



g) Steel G - 25°C/min

h) Steel H - 110°C/min

Fig. 2. cont'd.



i) Steel H - 175°C/min

Fig. 2 Microstructures of Gleeble flash-butt weld simulations at cooling rates listed below:

a) Steel A - 750°C/min
b) Steel C - 110°C/min
c) Steel D - 60°C/min
d) Steel D - 100°C/min
e) Steel F - 60°C/min
f) Steel G - 10°C/min
g) Steel G - 25°C/min
h) Steel H - 110°C/min
i) Steel H - 175°C/min

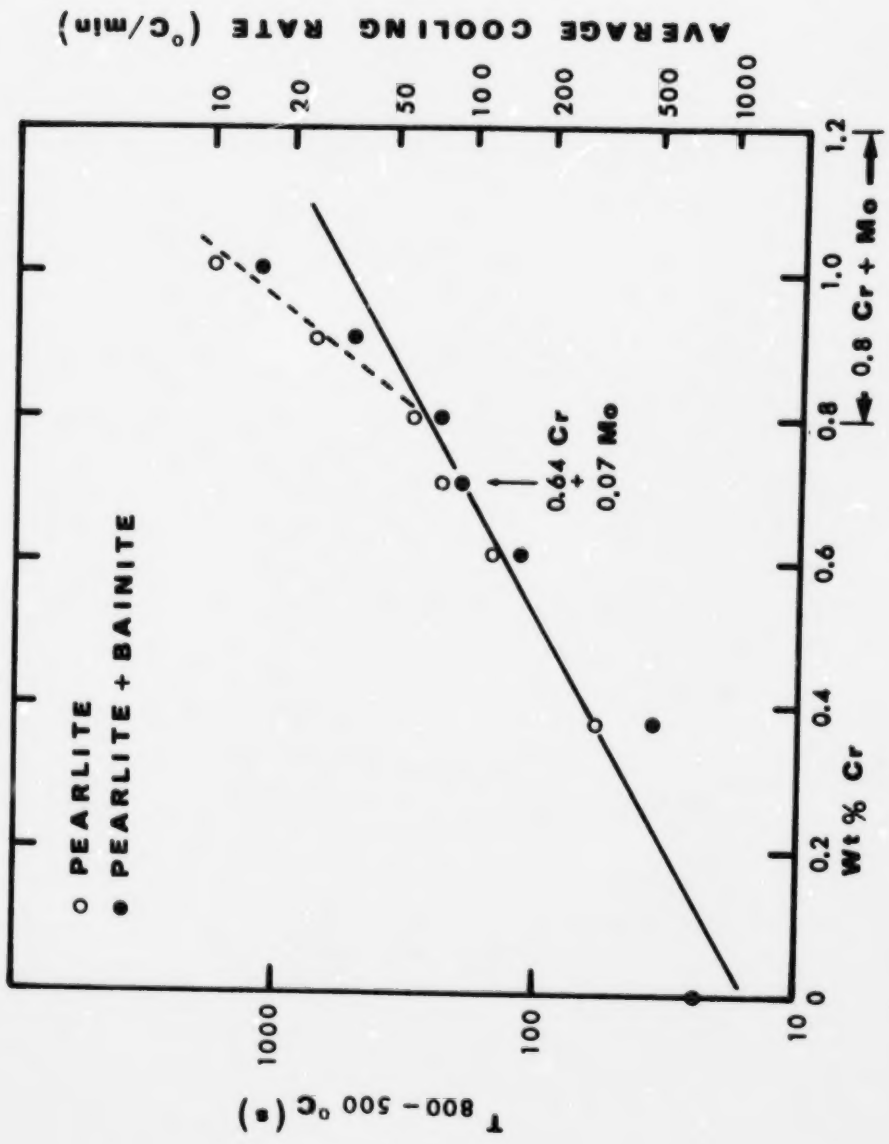


Fig. 3 Effect of Cr and Mo content on the critical cooling rate necessary to obtain a fully pearlitic structure.